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Rapid Communication

'Direct' evidence for water (H_2O) in the sunlit lunar ambience from CHACE on MIP of Chandrayaan I

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ABSTRACT

Direct detection of water in its vapour phase in the tenuous lunar environment through *in situ* measurements carried out by the Chandra's Altitudinal Composition Explorer (CHACE) payload, onboard the Moon Impact Probe (MIP) of Chandrayaan I mission vindicates the presence of water on the surface of the moon in form of ice at higher lunar latitudes inferred from IR absorption spectroscopy, (especially that of OH), by the Moon Mineralogy Mapper (M^3) of Chandrayaan I. The quadrupole mass spectrometer based payload, CHACE, sampled the lunar neutral atmosphere every 4 s with a broad latitudinal (~40°N to 90°S, with a resolution of ~0.1°) and altitudinal (from 98 km up to impact on the lunar surface with a resolution of ~0.25 km) coverage in the sunlit side of the moon for the first time. These two (CHACE and M^3) complementary experiments are shown to collectively provide unambiguous signatures for the distribution of water in solid and gaseous phases in Earth's moon.

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1. Introduction

The presence of water, or its derivatives in the lunar surface had been a subject matter of intense debate and research in the recent times. More so, after the first indication of water in the form of frozen ice in the permanently shadowed polar regions by the Clementine mission of NASA (Nozette et al., 1996), the topic got revived and the basic question whether the moon is really 'bone dry', came up again. Once the speculation and indirect inferences have been made, finding suitable direct evidences has become of paramount importance. All the more so, when the whole facet of future lunar exploration may be decided based on the availability water. Finding water or its derivatives therefore had been one of the fundamental scientific objectives of the recent lunar missions, like, Change-1 of China, Kaguya of Japan, Chandrayaan-I of India and the most recent Lunar Reconnaissance Orbiter (LRO) of the USA. Of all the four, Chandrayaan-I and LRO had carried along with them the Moon Impact Probe (MIP) and LCROSS respectively, which were released from the mother space craft and made to impact the polar regions of the moon. While the former was designed to carry out measurements during its descent, the latter was intended to create a deep impact crater and the ejecta due to the impact were to be analyzed. At the time of revising this paper LCROSS/LRO combination had confirmed the presence of water ice deeply buried in the permanently shadowed regions of the South Pole with soon-to-come more exciting results.

The most sensational finding from the Moon Mineralogy Mapper (M^3), an experiment from the USA on Chandrayaan-I had been the clear tell-tale signature of the presence of OH/ H_2O in the top few millimetres of the lunar regolith, over an extended region preferably at higher latitudes (Pieters et al., 2009). The inferences were arrived at through absorption spectroscopy in the 2.8–3 micron IR band. Though M^3 response was limited to 3 microns, just falling short of the peak of the absorption feature of water/ice, the signatures were unambiguous and were supported by the results from the Deep Impact Probe, while it was passing the moon on its way and also the Cassini space craft during the fly by when it focused on some of the Apollo landing sites for calibration purposes (Sunshine et al., 2009; Roger, 2009). In the light of these important findings and inferences, any direct measurement of H_2O would add further credence to the whole of lunar science. The result reported here-in from the Chandra's Altitudinal Composition Explorer (CHACE) on the Moon Impact Probe of India's Chandrayaan-I just does that by providing valuable information directly on the relative concentration of H_2O in the 'sunlit' lunar atmosphere through unique neutral composition measurements. The Moon Impact Probe, a micro satellite by itself, carried three experiments viz., Radar Altimeter,

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a Visible Imaging Camera, and an extremely sensitive neutral mass spectrometer (CHACE). The ‘first of its kind’ of results providing the altitudinal/latitudinal neutral composition of the tenuous lunar atmosphere during the lunar day have been obtained and the results pertaining to water (H_2O) form the subject matter for this communication.

2. Data base

The basic data pertaining to this paper is from CHACE, a quadrupole mass spectrometer, with a mass range of 1–100 amu, with an electron multiplier in its detector stage and having a partial pressure sensitivity of $<10^{-13}$ torr and nearly nine orders of magnitude dynamic range. It had a mass resolution of better than 1 amu all through its entire mass range and scanned the whole range in 4 s. On 14 November, 2008, as a part of the Moon Impact Probe (MIP), CHACE was switched on 20 min before its actual release, over a lunar latitude of ~40°N, when Chandrayaan-I was orbiting ~98 km. The Moon Impact

Probe (MIP) was released after some manoeuvre, at 13.3°S, 14°E so as to impact at a designated point in the South Pole region. Fig. 1 depicts the ground track of MIP. En route, CHACE had obtained data on the neutral composition with an unprecedented altitudinal resolution of ~250 m and a latitude resolution of 0.1 deg. In all, over 650 spectra have been acquired. CHACE had shown clearly the presence of 18 amu corresponding to water molecules right from the beginning, revealing it to be the most dominant of the species. However, one has to observe caution as 16, 17 and 18 amu are the most likely constituents of instrumental origin and separating out those corresponding to the lunar origin is extremely difficult in the absence of any further reference like say, a sample spectra en route to the moon. Since CHACE is a neutral mass spectrometer based on a hot filament ion source, it takes finite time of ~25 min to stabilise, putting stringent demands on the limited MIP resources if it had to be operated en route. Therefore the present experiment essentially turned out to be a ‘one shot’ affair. While analyzing the data with the above said constraint, the first results from the Moon Mineralogy Mapper (M^3), indicating the deposition of ice, the concentration of which showed a steady increase towards the pole is considered to vindicate the inferences from CHACE. Though M^3 is an imaging instrument with unprecedented spectral imaging

capability, the emphasis there- had been detecting water ice on the lunar surface. On the other hand, the CHACE in the MIP of Chandrayaan-I was designed to give the relative abundance of H_2O in its vapour phase with the extremely high sensitivity of partial pressure detection capability $<10^{-13}$ torr and also to provide very high altitudinal/latitudinal (250 m/0.1 deg) resolution as the MIP descended and raced towards the south pole. In a way, the results from CHACE and M^3 are complementary as the results from the latter pertaining to solid ice could in all probability be the source for water vapour concentration detected by CHACE.

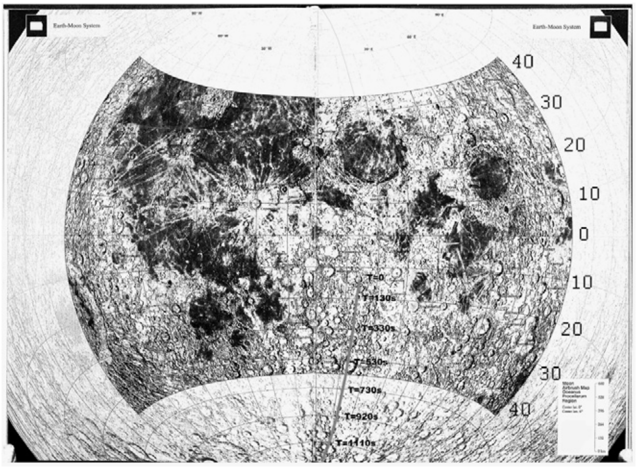

Fig. 1. The projected ground track over the Lunar atlas (Raymond (2001), *The Compact NASA Atlas of the Solar System*) of the Moon Impact probe after its release from the mother Space Craft Chandrayaan-1 as it raced towards the South Pole. The MIP was released on 14th November 2008.

3. Results

Fig. 2 depicts a sample spectrum obtained by CHACE at an altitude of ~97 km just after it had been released from the main orbiter–Chandrayaan-1 highlighting the capability of the instrument and also the quality of data. The Lunar ALSEP cold cathode gauge and the LACE (Lunar Atmosphere composition Experiment) of the Apollo series which provide the only authentic measurements available till recently had indicated a possible upper limit of 10^{-9} torr for the dayside pressures (Alan Stern, 1999 and the references therein). However, there were no direct measurements available to confirm the above inference due to the limited dynamic range of those instruments and due to the eventual detector saturation. While configuring CHACE this basic information had been kept in mind and it was ensured that the dynamic range of the instrument was kept as high as possible, in this case covering around nine orders of magnitude with both the Faraday cup and the electron multiplier put together. Interestingly the inbuilt ionization gauge revealed pressures in the range of 10^{-7} torr much higher than anticipated in a way explaining why the earlier detectors were saturated. Independent cross calibration of the CHACE ionization gauge in the laboratory before flight with other gauges had revealed good agreement within the experimental uncertainties. It should be noted that it is impossible to maintain a pressure difference of two orders of magnitude even in a closed system unless one takes recourse to differential pumping methods. It is all the more difficult when the probe is exposed to deep space vacuum with infinite pumping capacity Any amount of out gassing would not be able to produce and maintain such large differential pressures in space. Therefore the order of magnitude for the dayside pressures should essentially correspond to the level of 10^{-7} torr. An experiment with such large dynamic range in an orbiter that periodically crosses the day and night sides alone could provide an unambiguous answer.

In the present experiment, the sum of all the partial pressures due to the dominant species have been normalised to the ionization gauge readings at that instant and the relative amplitudes with respect to the normalised values have been depicted in Fig. 2 in a linear scale. The linear scale has been chosen to highlight the relative variation of the dominant species. It had been mentioned earlier that the instrument was switched on 20 min prior to the actual release of MIP. It had been verified by cross checking with all the house keeping parameters including the filament voltage and source current that CHACE had indeed stabilized when the MIP was over the latitude of 20°S implying that the uncertainties in the relative measurements were $<10\%$. Though one could still investigate the relative composition from the start of the experiment, only the data, starting from 20°S (at 97 km) to the impact point in the south pole are considered for the present analysis; that too, we restrict ourselves only to the variability of amu 18 (H_2O). Fig. 3 shows the variation of the representative partial pressure of 18 amu with latitude. In getting these partial pressures, due care has been taken to account for the mass discrimination factor of the quadrupole analyzer and also the mass dependence of the electron multiplier gain in addition to corrections pertaining to the dominant ambient gas for the ionization gauge. Another important factor would be the steep latitudinal temperature gradient along the lunar latitude that

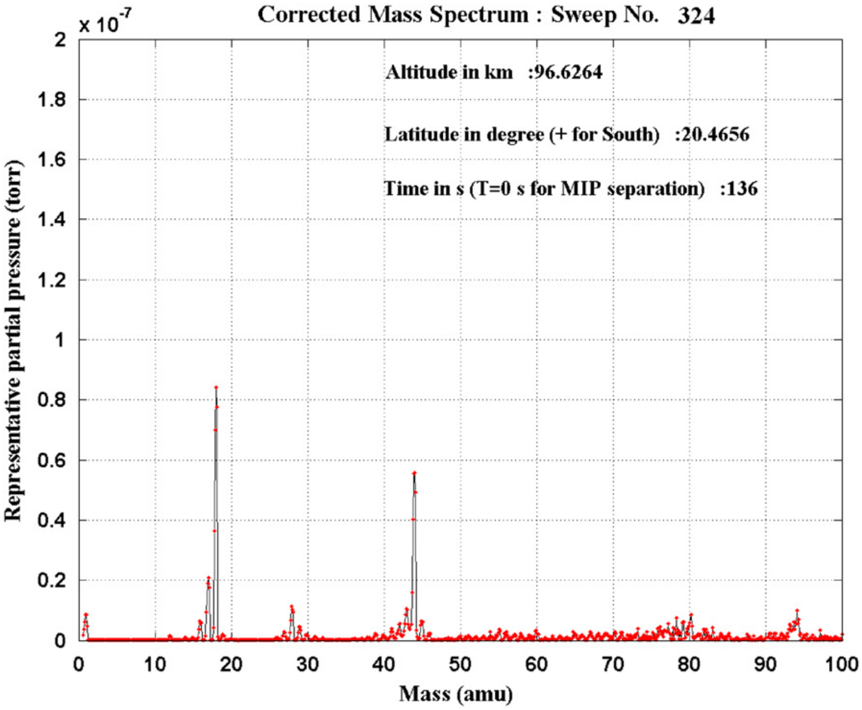

Fig. 2. Sample mass spectrum corresponding to 97 km after the release of MIP highlighting the capability of the instrument, the quality of data and also the presence of H_2O as one of the dominant species.

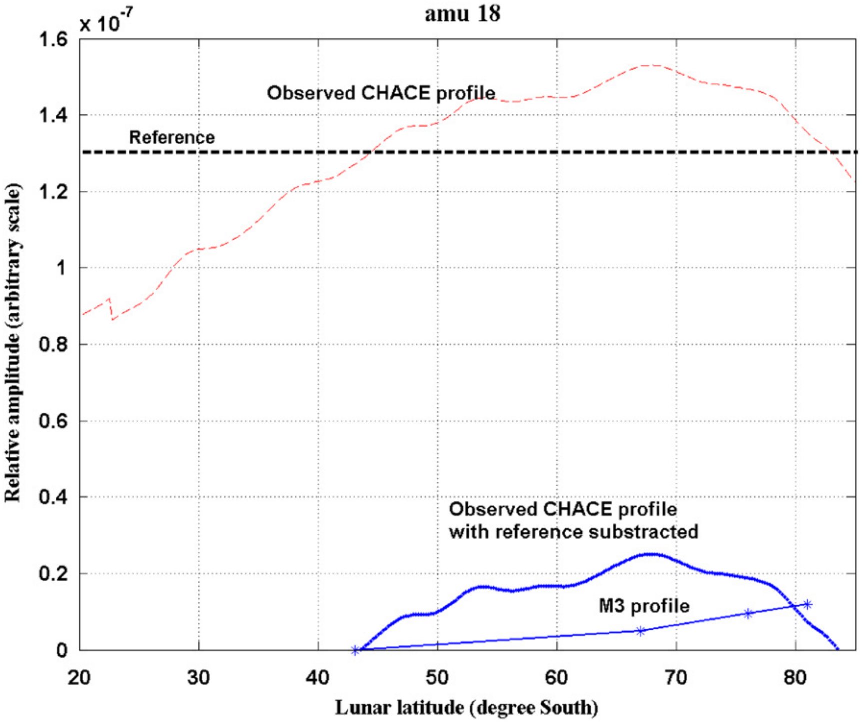

Fig. 3. The latitudinal/altitudinal variation as observed by CHACE from 20°South to the poles highlighting a steady increase in the H_2O concentration that maximized around 60–70°S latitude. The relative concentration of water-ice as detected by M^3 depicting the steady increase in the concentration as one moved towards the poles. Treating the latitude of 43.1°S as the reference beyond which M^3 had started detecting water ice, the relative variation of H_2O as seen by CHACE is also depicted highlighting the complementary nature of the measurements from CHACE and M^3.

is likely to vary from ~400 K over the equator to ~100–150 K over the poles (Alan Stern, 1999). This sort of temperature variation would manifest in the altitudinal variation of the species concerned as the moon is believed to have a Surface Boundary Exosphere (SBE), permitting each one of the atmospheric constituents, to have their own scale height – i.e., to have their own atmosphere occupying the same volume (Alan Stern, 1999). CHACE results reveal that H_2O concentrations registered an increase by a factor of 2 from a lunar latitude of 20°S–∼70°S, beyond which it decreased to ∼70% of its peak value (Fig. 3). Going by the concept of Surface Boundary Exosphere and accounting for the temperature gradient of 400–150 K from the equator to the poles (which has once again been confirmed independently using the altitude profile of 36 Ar from CHACE itself – (not shown in figure for the sake of brevity) – with an assumption of 400 K over the equator), the concentration of amu 18 is not expected to vary by $>10\%$ with altitude/ latitude. Further, out gassing from the hot ion source in particular or from the instrument in general has to be assessed and accounted for before any conclusions are drawn. The instrument had been exposed to deep vacuum for more than three weeks as the spacecraft raced to the moon (October 22–November 14) before getting switched on. After switching on, all the ion source parameters including the emission current had been allowed to stabilise which implies the filament temperature and the overall ion source temperatures have attained stability. This would imply that out gassing, if any, from the ion source would remain constant acting as a steady background. If there had been any out gassing of H_2O or its derivatives then their concentrations should have remained constant throughout the trajectory of short duration missions like the MIP. The very fact that the H_2O concentration initially registered an increase by a factor of two in the latitude region of 20°S–70°S only to decrease to 70% of its peak value beyond 70°S latitude highlights that the variations recorded are of lunar origin. Both the increase (20°S–70°S) and decrease ($>70°$S) in concentration of H_2O should be treated alike and looked into in the light of probable steady background due to out gassing if any. Therefore, from Fig. 3 one could conclude that there has to be a significant source of H_2O. However, when it comes to the partial pressure, as mentioned earlier, it is difficult to separate out the lunar contribution alone from the measured mass spectra, except for the clue that any contribution of instrumental origin is expected to be present all though with the same relative contribution, essentially providing a dc bias to the estimated partial pressures. Now that the first results have been published from the Moon Mineralogy Mapper (M^3), which is a spectroscopic measurement free from contamination / out gassing, from the instrument, these can be taken as ‘the first cut’ reference for the CHACE results. The M^3 data with its present sensitivity level did not reveal any trace of water ice up to ∼43°S latitude and clearly depicted its build up as one moved towards the pole (Pieters et al., 2009). The latitudinal variation as inferred by them has been redrawn in Fig. 3. The relative variation of representative partial pressures as detected by CHACE, with respect to 43°S value that is taken as the reference based on M^3 data, is also shown in the figure. It is interesting to see that CHACE registered a steady increase in H_2O concentration reaching a maximum around 65–70°S beyond which there is a tendency to decrease, while the M3 data showed a monotonic increase. The nearly opposite behaviour of CHACE and M^3 could be explained as follows. The CHACE directly samples the tenuous gaseous atmosphere while M^3 looks for water ice on the top layers of the lunar regolith. If the water ice acts as the source due to, say, sublimation, which would be a strong function of temperature in the prevailing ultra high vacuum condition, then, in the absence of fresh sources during the measurement phase, the increase/decrease in the concentration measured by CHACE should be at the cost of what M^3 has detected in the form of ice. There seems to be consistency in their behavioural pattern. This result clearly vindicates the direct measurement of H_2O in its gaseous form by CHACE. In this context, it is worth mentioning that some of the sample results from the LACE (Lunar Atmospheric Composition Experiment) in Apollo – 17 also revealed the clear presence of 18 amu along with several other constituents during sunrise time (Hoffman et al., 1973) all of which eventually got into saturation in the sunlit side. These constituents, barring the noble gases were treated to be due to out-gassing from the instrument and the surroundings. On the other hand, CHACE results clearly show that, the above out look need not be the case and suggest that it may be worth revisiting the Apollo data, in spite of them corresponding to a single location unlike the case of CHACE. The associated build up of the concentration of the different species with the changes in the solar aspect angle like what has been shown for Argon (Hodges, 1975), though restricted only up to sunrise periods, would still provide more clues pertaining to the lunar ambience. Further detailed analysis pertaining to the other constituents registered in CHACE, are in progress.

4. Conclusion

The CHACE experiment on the Moon Impact Probe of Chandrayan-I, made a direct detection of H_2O in the tenuous lunar ambience complementing the Moon Mineralogy Mapper in the same mission. Having established the complementary nature of the results from these two experiments, the inherent higher sensitivity of the CHACE enables one to extend the latitudinal coverage down to 20°S (Fig. 3). These results further substantiate those obtained from the Deep Impact Probe revealing extended regions of water content. The trend of increasing concentration of H_2O maximizing ∼60–70°S latitude is clearly brought out, which itself is believed to be due to the temperature variation and the consequent changes in the sublimation rate with respect to latitude and also to the availability of water ice. Though a ‘one shot’ measurement, the CHACE results could still be treated as to support the concept of migration of water towards the cooler poles to be eventually buried there as frozen ice.

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